

Neutrino-triggered asymmetric magnetorotational mechanism for pulsar natal kick

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Abstract

The sterile neutrino mechanisms for natal neutron star kicks are reanalyzed. It is shown that the magnetic field strengths needed for obtaining the observable values of kicks were underestimated essentially. Another mechanism with standard neutrinos is discussed where the outgoing neutrino flux in a supernova explosion with a strong toroidal magnetic field generation causes the field redistribution in “upper” and “lower” hemispheres of the supernova envelope. The resulting magnetic field pressure asymmetry causes the pulsar natal kick.

1 Pulsar proper motion problem

The problem of large proper velocities of pulsars, born in supernova explosions (pulsar kick), has been discussed for more than 40 years. The total list of publications with the observational data is very long. We indicate here only the first papers [1, 2] where the problem was put, and the papers where the data were summarized with the samples of 99 pulsars [3] and of 233 pulsars [4]. Average speed for the sample of 233 pulsars [4] was estimated at the level of 400 km/s, with more than 15 % having velocities greater than 1000 km/s. The two fastest pulsars PSRs B2011+38 and B2224+64 have ~ 1600 km/s.

It is important that a correlation was finally established between the directions of pulsar velocities and of rotation axes. Initially, a conclusion was made in the paper [5], based on an analysis of the set of 29 pulsars, that mechanisms predicting a correlation between the rotation axis and the pulsar velocity were ruled out by the observations. However, in the paper [6] strong observational evidence was presented for a relationship between the direction of a pulsar’s motion and its rotation axis. Analysing a set of 25 pulsars which are younger than the ones taken in Ref. [5], the authors [6] conclude that 10 pulsars show an offset between the velocity vector and the rotation axis, which is either less than 10^0 or more than 80^0 , a fraction that is very unlikely by random chance.

Obviously, the reason for the initial kick is a kind of an asymmetry in a supernova explosion, but the nature of it has not yet disclosed. There were many attempts to explain this asymmetry.

Numerous attempts to describe the effect in the hydrodynamics of a supernova explosion do not explain the large speeds. Three-dimensional simulation of the explosion with the assumption of initial asymmetry in the supernova core before the collapse, which increases during the collapse, leads to the velocity of a pulsar not more than 200 km/s [7]. Multidimensional simulation by H.-T. Janka e.a. [8] where the explosion anisotropies develop chaotically, resulted in a possible pulsar velocity of 10^3 km/s. However, there was no correlation between the direction of pulsar velocity and the rotation axis direction [6] in this approach.

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Along with the hydrodynamic approach, there were several different ideas to explain the velocities of pulsars, but all of them operated at speeds of scale of 100 km/s:

- i) evolution of close binary systems [9];
- ii) acceleration of a pulsar within a few months after the explosion due to asymmetric electromagnetic radiation caused by the inclination of the magnetic moment with respect to the axis of rotation and the displacement of the center of the star [10];
- iii) asymmetric radiation of neutrinos (antineutrinos) in a collapse via the URCA-processes in a strong magnetic field of the scale of $10^{14} - 10^{15}$ G in a supernova core [11–13].

The neutrino mechanism looks the most interesting. It is known that neutrinos carry away 99 % of the total supernova energy $E \sim 3 \times 10^{53}$ erg. When the asymmetry is of $\sim 3\%$, neutrinos carry the momentum of $\sim 0.03 E/c$. The compact explosion remnant, a neutron star with a mass $\sim 1.4M_\odot$, gets the same momentum. In this case, its velocity can be easily estimated as ~ 1000 km/sec.

However, neutrinos produced in the electroweak processes have small mean free paths in matter of the central part of a supernova and may not cause high-velocity pulsars [14–16].

A lively discussion was generated by the idea [17], under which the neutrino flux asymmetry from a protoneutron star arose due to neutrino oscillations in matter and intensive magnetic field. The neutrinosphere for ν_τ lies inside the neutrinosphere for ν_e , and the resonant transition $\nu_e \rightarrow \nu_\tau$ is possible under certain conditions in the region between the neutrinospheres, where ν_e are entangled in the medium while ν_τ are “free” to depart. Hence the surface of the resonant transition becomes an effective neutrinosphere for ν_τ . In the presence of a magnetic field, this sphere is deformed along the field. Due to the temperature dependence on the radius, the anisotropy of the energy flux carried away by neutrinos, arises. This should cause the kick of the nascent neutron star.

The idea of the pulsar kick due to deformed neutrinosphere [17] raised, however, serious criticism [18]: after the neutrinosphere deformation, the surfaces of the constant temperature would be deformed also, because just neutrinos provided a thermal equilibrium. And the main problem of the model became clear soon: the existence of neutrinos with the mass ~ 100 eV was needed. Established restriction on the neutrino mass, $m_\nu < 2$ eV, “closed” the model.

There were also attempts to explain large space velocities of young pulsars with using of some possible non-standard properties of neutrinos. For example, a mechanism was proposed by E. Akhmedov et al. [19], of the resonant spin-flavour precession of neutrinos with a transition magnetic moment in the magnetic field of a supernova. The asymmetric emission of neutrinos was caused by the distortion of the resonance surface due to matter polarisation effects in the supernova magnetic field. The requisite values of the field strengths were declared to be of order 10^{16} G, and neutrino parameters were taken within the existing experimental bounds. However, as was mentioned in the paper [18], in fact the magnetic fields were required in the model [19] more than an order of magnitude larger.

2 The initial pulsar kick and sterile neutrinos

The sterile neutrinos came on stage in Ref. [20] (see also [21] for details), where the same deformed by magnetic field neutrinosphere as in Ref. [17] was discussed, but instead of oscillations $\nu_{\mu,\tau} \leftrightarrow \nu_e$, the transitions were considered into “heavy” sterile neutrinos $\nu_{\mu,\tau} \leftrightarrow \nu_s$. The attractiveness of the model was in an idea that the heavy sterile neutrino (with the mass-scale of a few keV) simultaneously solved two problems: providing an initial velocity of pulsars they could also play the role of dark matter.

However, when we have reproduced calculations performed in Refs. [20,21] we have obtained that the result for the asymmetry was overvalued in [21] at 15 times. In other words, for

the declared asymmetry, the necessary magnetic field strength should be 15 times larger: not $\sim 3 \times 10^{16}$ G but $\sim 4.6 \times 10^{17}$ G.

Another scenario of using sterile neutrinos for the pulsar kick explanation with off-resonance transitions was developed in Ref. [22]. Sterile neutrinos could be born in β -processes due to the neutrino mixing, but the process is suppressed because of smallness of the mixing angle. However, they can take a significant amount of energy due to two factors:

- (1) within the core, neutrinos have energies ~ 150 MeV, which is much greater than the energy of active neutrinos ~ 20 MeV, emitted from a neutrinosphere;
- (2) the emission occurs from the volume, not from the surface.

In the presence of a magnetic field, neutrinos are emitted asymmetrically, and this asymmetry is maintained because sterile neutrinos are not absorbed, but fly away freely, unlike the situation in the approach of Refs. [11–13]. However, as our analysis shows, the asymmetry was overvalued in [22] at 40 times at least. In other words, for the declared in Ref. [22] asymmetry, the magnetic field strength needed should be 40 times larger: not $\sim 10^{16}$ G but $\sim 4 \times 10^{17}$ G. In our opinion, the authors [22] made a mistake in calculation of the value k_0 defined in Eq. (9) and presented in Fig. 2 of [22]. By the way, the authors call the value k_0 as the fraction of electrons in the lowest Landau level, while in fact it is the fraction of electron energy squared in the lowest Landau level, defining an asymmetry of the neutrino–electron interaction in β -processes. It can be shown that the result of the paper [22] is wrong, both by direct numerical calculation and analytically. Really, using Eqs. (9), (10) of Ref. [22] one can transform the expression for the value k_0 with a good accuracy to the form:

$$k_0 \simeq \frac{eB}{2T^2} \frac{J_2(\mu_e/T)}{J_4(\mu_e/T)}, \quad (1)$$

where B is the magnetic field strength, μ_e and T are the chemical potential and the temperature of electrons, and $J_n(\eta)$ are the Fermi integrals:

$$J_n(\eta) = \int_0^\infty \frac{x^n dx}{e^{x-\eta} + 1}. \quad (2)$$

Depending on the electron chemical potential and the magnetic field strength, the value k_0 is overestimated in Fig. 2 of [22] by the factor from 40 to 90.

In the recent e-print [23], C. Kishimoto presented a detailed numerical analysis of the transformation of active neutrinos to sterile neutrinos through an MSW-like resonance in the protoneutron star, in order to provide the pulsar kick. However, after correcting a numerical mistake in the version 1 of the e-print, it can be seen that the magnetic field strength needed for a desirable effect should be taken of the order of 10^{18} G.

3 Back to standard neutrinos?

A reasonable question arises: if we really need such strong magnetic fields to provide a natal neutron star kick with sterile neutrinos, isn't it possible to manage with standard neutrinos?

As it was already mentioned, an asymmetry of the standard neutrino radiation in a strong magnetic field is not a new topic. For example, in the series of papers by our group [24–26] the asymmetry of neutrino emission in a strong magnetic field:

$$A = \frac{|\sum_i \mathbf{p}_i|}{\sum_i |\mathbf{p}_i|} \quad (3)$$

was analysed, which arised due to parity violation in the neutrino-electron and neutrino-nucleon processes. In a strong field of the poloidal type [27–29], only due to the process $\nu \rightarrow \nu e^- e^+$ one

obtains [24]:

$$A \sim 3 \times 10^{-3} \left(\frac{B}{10^{16} \text{ G}} \right) \left(\frac{\bar{E}}{20 \text{ MeV}} \right)^3 \left(\frac{\Delta\ell}{20 \text{ km}} \right), \quad (4)$$

where $\Delta\ell$ is the characteristic size of the region where the field strength varies insignificantly, and \bar{E} is the neutrino energy averaged over the neutrino spectrum. The asymmetry is seen to be not enough to provide the observable neutron star kick with such field strength.

It should be noted that the mechanism is known of essential enhancement of the magnetic field strength during a supernova explosion. It is the magnetorotational supernova by G.S. Bisnovatyi-Kogan [30,31], a model for generation of the toroidal magnetic field. A poloidal magnetic field being enhanced during the supernova core collapse and being frozen in plasma, due to the differential rotation, generates a strong toroidal magnetic field which could be in order of magnitude greater than the original poloidal field.

4 Tangential Neutrino Force

Let us remind what is a possible integral effect of neutrinos on a magnetized plasma. Consider first the neutrino-electron processes [25]. A complete set of these processes in plasma,

$$\nu e^\mp \rightarrow \nu e^\mp, \quad \nu \rightarrow \nu e^- e^+, \quad \nu e^- e^+ \rightarrow \nu, \quad (5)$$

lead to the energy and force neutrino flux impact on plasma:

$$(\dot{\mathcal{E}}, \mathcal{F}_z) = \int (P - P')_{0,z} dn_\nu dW, \quad dn_\nu = \frac{d^3P}{(2\pi)^3} \frac{\Phi(\vartheta, R)}{e^{(E-\mu_\nu)/T_\nu} + 1}. \quad (6)$$

Here, dW is the total differential probability of all the processes specified in (5), P and P' are the initial and final neutrino four-momenta, the z axis is directed along the magnetic field, dn_ν is the initial neutrino density, μ_ν and T_ν are the effective chemical potential and the spectral temperature of the neutrino gas, and the function $\Phi(\vartheta, R)$ determines the neutrino angular distribution, depending on the angle ϑ between the neutrino momentum and the radial direction in the star and on the distance R from the center of the star. It should be noted that Eq. (6) can be used for evaluating the integral effect of neutrinos on plasma in the conditions of not very dense plasma, e.g. of a supernova envelope, when an one-interaction approximation of a neutrino with plasma is valid.

Spectral temperatures for different types of neutrinos are estimated to be [32]:

$$T_{\nu_e} \simeq 4 \text{ MeV}, \quad T_{\bar{\nu}_e} \simeq 5 \text{ MeV}, \quad T_{\nu_{\mu,\tau}} \simeq T_{\bar{\nu}_{\mu,\tau}} \simeq 8 \text{ MeV}. \quad (7)$$

The probability of the β processes ($\nu_e + n \leftrightarrow e^- + p$) is substantially higher than that for neutrino-electron processes, so the β processes dominate in the energy balance. As a result of neutrino heating the plasma, temperature should be very close to the spectral temperature of the electron neutrinos, $T \simeq T_{\nu_e}$.

As it was shown in Refs. [25], the main contributions into the values $\dot{\mathcal{E}}$ and \mathcal{F}_z in (6) were made by μ and τ neutrinos and antineutrinos (as a result of the conservation of CP , neutrinos and antineutrinos push the plasma in the same direction). This is because in the vicinity of the ν_e neutrinosphere the spectral temperatures of the other types of neutrinos differ substantially from the plasma temperature $T \simeq T_{\nu_e}$.

For numerical estimates we can conveniently express the contribution from ν - e -processes with $\bar{\nu}_e$, $\nu_{\mu,\tau}$, $\bar{\nu}_{\mu,\tau}$ into the values $\dot{\mathcal{E}}$ and \mathcal{F}_z in the following form:

$$(\dot{\mathcal{E}}, \mathcal{F}_z)_{\nu_i} \simeq \mathcal{A} \left[\left(C_V^{(i)} \right)^2 + \left(C_A^{(i)} \right)^2, 2C_V^{(i)} C_A^{(i)} \right] \psi(T_{\nu_i}/T), \quad (8)$$

where

$$\mathcal{A} = \frac{12 G_F^2 e B T^7}{\pi^5} = \left(\frac{B}{10^{16} \text{G}} \right) \left(\frac{T}{4 \text{MeV}} \right)^7 \times \begin{cases} 1.6 \cdot 10^{30} \frac{\text{erg}}{\text{cm}^3 \cdot \text{s}}, \\ 0.55 \cdot 10^{20} \frac{\text{dyne}}{\text{cm}^3}, \end{cases} \quad (9)$$

The electroweak constants $C_V^{(i)}, C_A^{(i)}$ of the effective Lagrangian of the neutrino-electron interaction in Eq. (8) are:

$$C_V^{(e)} = \frac{1}{2} + 2 \sin^2 \theta_W, \quad C_A^{(e)} = \frac{1}{2}, \quad C_V^{(\mu, \tau)} = -\frac{1}{2} + 2 \sin^2 \theta_W, \quad C_A^{(\mu, \tau)} = -\frac{1}{2}. \quad (10)$$

The temperature dependent function has the form:

$$\psi(\tau_i) = \frac{\tau_i^7}{6} \int_0^\infty \frac{y^2 dy}{e^{\tau_i y} - 1} \left[e^{(\tau_i - 1)y} - 1 \right], \quad \psi(\tau_i) \Big|_{\tau_i \rightarrow 1} \simeq \frac{\pi^4}{90} (\tau_i - 1). \quad (11)$$

For electron antineutrinos one obtains $\psi(1.25) \simeq 0.82$, while for muon and tau neutrinos and antineutrinos the function is $\psi(2) \simeq 38.5$.

A combined effect of all types of neutrinos interacting with electron-positron plasma is:

$$\mathcal{F}_B^{(\nu e)} \simeq 3.6 \times 10^{20} \left(\frac{B}{10^{16} \text{G}} \right) \left(\frac{T}{4 \text{MeV}} \right)^7 \frac{\text{dyne}}{\text{cm}^3}. \quad (12)$$

Contribution of the neutrino-nucleon processes was evaluated in Refs. [26]. For the parameters of the shell of a supernova: $Y_e \simeq 0.2$, $\rho \simeq 10^{11-12} \text{ g/cm}^3$, one obtains (νN means both urca-processes and νN -scattering)

$$\mathcal{F}_B^{(\nu N)} \simeq 2.4 \times 10^{20} \left(\frac{B}{10^{16} \text{G}} \right) \frac{\text{dyne}}{\text{cm}^3}. \quad (13)$$

It is important that the contributions of both neutrino-electron and neutrino-nucleon processes are of the same sign. The total neutrino force density is:

$$\mathcal{F}_B^{(total)} \simeq 0.6 \times 10^{21} \left(\frac{B}{10^{16} \text{G}} \right) \frac{\text{dyne}}{\text{cm}^3}. \quad (14)$$

Note that the force density (14) is five orders of magnitude lower than the density of the gravitational force and thus negligibly influences the radial dynamics of the supernova shell. However, when a toroidal magnetic field [30,31] is generated in the shell, the force (14) directed along the field can fairly rapidly (within times of the order of a second¹) lead to substantial redistribution of the tangential plasma velocities. Then in two toroids in which the magnetic field has opposite directions, the tangential neutrino acceleration of the plasma will have different signs relative to the rotational motion of the plasma. This effect can then lead to substantial redistribution of the magnetic field lines, concentrating them predominantly in one of the toroids. This leads to considerable asymmetry of the magnetic field energy in the two hemispheres and may be responsible for the asymmetric explosion of the supernova which could explain the discussed phenomenon of high intrinsic pulsar velocities. In our view it is interesting to model the mechanism for toroidal magnetic field generation taking into account the neutrino force action on the plasma both via neutrino-nucleon and neutrino-electron processes.

¹We know that the cooling stage of a supernova shell, known as the Kelvin-Helmholtz stage, lasts for around 10 s.

5 Neutrino-triggered magnetorotational pulsar natal kick

Considered neutrino processes in toroidal magnetic field which is frozen in plasma, provide the angular acceleration for an element of plasma at a distance R from the rotation axis:

$$\dot{\Omega} = \frac{\mathcal{F}}{\rho R} \simeq 1.2 \times 10^3 \frac{1}{\text{sec}^2} \left(\frac{B}{10^{16} \text{G}} \right). \quad (15)$$

It means that during the time ~ 1 sec the increase of the angular velocity is

$$\Delta\Omega \sim 10^3 \frac{1}{\text{sec}} \left(\frac{B}{10^{16} \text{G}} \right). \quad (16)$$

In the one hemisphere, the angular acceleration coincides with the direction of the initial rotation, while in another hemisphere, they are opposites. A neutrino flux, pushing the plasma, torques the toroids in different directions.

Thus, three stages of a pulsar kick can be identified:

- i) pre-supernova core is collapsing with rotation during 0.1 sec when a strong toroidal magnetic field is generated due to the differential rotation;
- ii) the neutrino outburst, pushing the plasma by the tangential force along the toroidal magnetic field which is frozen in plasma, leads to a magnetic field asymmetry: the field strength is enhancing in one hemisphere and is decreasing in another one, during ~ 1 sec;
- iii) the pressure difference arising in the two hemispheres, causes the kick to a core.

According to the momentum conservation, an energetic plasma jet must be formed opposite to the pulsar velocity direction ².

Surely, a detailed multi-dimensional numerical simulation of the process is needed. Let us estimate in order of magnitude what to expect.

A pressure difference arising in the two hemispheres can be evaluated as:

$$\Delta p \simeq \frac{B^2}{8\pi} = \frac{(eB)^2}{8\pi\alpha}, \quad (17)$$

where $\alpha = 1/137$ is the fine-structure constant. The magnetic field pressure causes the plasma acceleration:

$$\frac{dV_{kick}}{dt} \simeq 1.6 \times 10^5 \frac{\text{km}}{\text{sec}^2} \left(\frac{B}{10^{16} \text{G}} \right)^2 \left(\frac{R}{20 \text{km}} \right)^2 \left(\frac{1.4 M_\odot}{M} \right) \sin 2\theta \Delta\theta, \quad (18)$$

where R, θ and $\Delta\theta$ are the parameters that characterize the region of a strong toroidal magnetic field, see Fig. 1.

Taking for estimation $\Delta\theta \sim 15^\circ \sim \frac{1}{4}$, $\theta \sim 45^\circ$ one obtains

$$\frac{dV_{kick}}{dt} \simeq 4 \times 10^4 \frac{\text{km}}{\text{sec}^2} \left(\frac{B}{10^{16} \text{G}} \right)^2 \left(\frac{R}{20 \text{km}} \right)^2 \left(\frac{1.4 M_\odot}{M} \right). \quad (19)$$

In fact, the acceleration is not a constant, and an expansion of the magnetic field volume, which reduces the magnitude of the field should be taken into account. The magnetic flux conservation provides: $pV^2 = \text{const}$.

Within the same geometry, one obtains:

$$V_{kick} \simeq 600 \frac{\text{km}}{\text{sec}} \left(\frac{B_0}{10^{16} \text{G}} \right) \left(\frac{R}{20 \text{km}} \right) \left(\frac{\Delta z}{5 \text{km}} \right)^{1/2} \left(\frac{1.4 M_\odot}{M} \right)^{1/2}, \quad (20)$$

where B_0 is the initial field strength, Δz is a distance traveled by a compact remnant of the explosion.

²This remark was made by Hans-Thomas Janka.

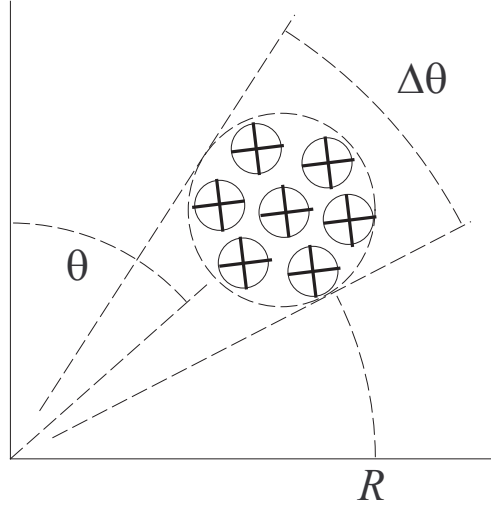


Figure 1: The region of a strong toroidal magnetic field.

6 Conclusions

- There are many mechanisms for pulsar natal kick, and the one using sterile neutrinos and proposed by A. Kusenko e.a. looks the most attractive. However, as the analysis shows, for the declared effect the magnetic field strength should be much larger, not $\sim 10^{16}$ G, but $\gtrsim 4 \times 10^{17}$ G.
- With such strong magnetic fields, it is possible to manage with standard neutrinos.
- As it was shown in the papers by our group, neutrino-electron and neutrino-nucleon processes in a strong magnetic field, cause the appearance of a force density acting on magnetized plasma along the field direction,

$$\mathcal{F}_B \simeq 0.6 \times 10^{21} \left(\frac{B}{10^{16} \text{G}} \right) \frac{\text{dyne}}{\text{cm}^3}.$$

- If the strong toroidal magnetic field is generated in the vicinity of the supernova core (magnetorotational supernova model by G.S. Bisnovatyi-Kogan), the neutrino flux, pushing the plasma, torques the toroids in different directions. In the one hemisphere, the additional angular acceleration coincides with the direction of the initial rotation, while in another hemisphere, they are opposites.

We stress that just the toroidal magnetic fields are considered which can be generated in order of magnitude greater than the poloidal fields used in other approaches.

- There arises the magnetic field asymmetry in the two hemispheres, and consequently the field pressure difference providing the pulsar kick acceleration:

$$\frac{dV_{kick}}{dt} \simeq 4 \times 10^4 \frac{\text{km}}{\text{sec}^2} \left(\frac{B}{10^{16} \text{G}} \right)^2 \left(\frac{R}{20 \text{ km}} \right)^2 \left(\frac{1.4 M_\odot}{M} \right)$$

and the kick velocity:

$$V_{kick} \simeq 600 \frac{\text{km}}{\text{sec}} \left(\frac{B_0}{10^{16} \text{G}} \right) \left(\frac{R}{20 \text{ km}} \right) \left(\frac{\Delta z}{5 \text{ km}} \right)^{1/2} \left(\frac{1.4 M_\odot}{M} \right)^{1/2}$$

- Because of large acceleration, a pulsar acquires big velocity during very short time, like in a shot. One should remember how he operated, being a child, with a cherry-stone after eating cherries: pressing it asymmetrically by fingers, he provided a big velocity to that compact object. So, we may consider a kind of “Cherry-Stone Shooting” mechanism for pulsar natal kick.
- According to the momentum conservation, an energetic plasma jet must be formed opposite to the pulsar velocity direction.
- A detailed multi-dimensional numerical simulation of the process is needed. We would believe it should confirm the effect.

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References

- [1] I. S. Shklovskii, *Astron. Zh.* **46**, 715 (1969) [*Sov. Astron.* **13**, 562 (1970)]
- [2] J. E. Gunn and J. P. Ostriker, *Astrophys. J.* **160**, 979 (1970).
- [3] A. G. Lyne and D. R. Lorimer, *Nature* **369**, 127 (1994)
- [4] G. Hobbs, D. R. Lorimer, A. G. Lyne and M. Kramer, *Mon. Not. R. Astron. Soc.* **360**, 974 (2005).
- [5] A. A. Deshpande, R. Ramachandran and V. Radhakrishnan, *Astron. Astrophys.* **351**, 195 (1999).
- [6] S. Johnston, G. Hobbs, S. Vigeland, M. Kramer, J. M. Weisberg and A. G. Lyne, *Mon. Not. R. Astron. Soc.* **364**, 1397 (2005).
- [7] C. L. Fryer, *Astrophys. J.* **601**, L175 (2004).
- [8] L. Scheck, K. Kifonidis, H.-T. Janka and E. Müller, *Astron. Astrophys.* **457**, 963 (2006).
- [9] J. R. Gott, J. E. Gunn, and J. P. Ostriker, *Astrophys. J. Lett.* **160**, L91 (1970).
- [10] E. R. Harrison and E. Tademaru, *Astrophys. J.* **201**, 447 (1975).
- [11] N. N. Chugai, *Pis'ma Astron. Zh.* **10**, 210 (1984) [*Sov. Astron. Lett.* **10**, 87 (1984)].
- [12] Yu. M. Loskutov, *Pis'ma v ZhETF* **39**, 438 (1984) [*JETP Letters* **39**, 531 (1984)]; *Teor. Mat. Fiz.* **65**, 141 (1985) [*Theor. Math. Phys.* **65**, 1066 (1985)].

- [13] O. F. Dorofeev, V. N. Rodionov and I. M. Ternov, Pis'ma v ZhETF **40**, 159 (1984) [JETP Letters **40**, 917 (1984)]; Pis'ma Astron. Zh. **11**, 302 (1985) [Sov. Astron. Lett. **11**, 123 (1985)].
- [14] A. Vilenkin, Astrophys. J. **451**, 700 (1995).
- [15] D. Lai and Y.-Z. Qian, Astrophys. J. **505**, 844 (1998).
- [16] P. Arras and D. Lai, Astrophys. J. **519**, 745 (1999).
- [17] A. Kusenko and G. Segrè, Phys. Rev. Lett. **77**, 4872 (1996).
- [18] H.-T. Janka and G. G. Raffelt, Phys. Rev. D **59**, 023005 (1998).
- [19] E. Kh. Akhmedov, A. Lanza and D. W. Sciama, Phys. Rev. D **56**, 6117 (1997).
- [20] A. Kusenko and G. Segrè, Phys. Lett. B **396**, 197 (1997).
- [21] A. Kusenko, Phys. Rep. **481**, 1 (2009).
- [22] G. M. Fuller, A. Kusenko, I. Mocioiu and S. Pascoli, Phys. Rev. D **68**, 103002 (2003).
- [23] C. Kishimoto, arXiv:1101.1304.
- [24] A. V. Kuznetsov and N. V. Mikheev, Phys. Lett. B **394**, 123 (1997); Yad. Fiz. **60**, 2038 (1997) [Phys. At. Nucl. **60**, 1865 (1997)].
- [25] A. V. Kuznetsov and N. V. Mikheev, Mod. Phys. Lett. A **14**, 2531 (1999); ZhETF **118**, 863 (2000) [JETP **91**, 748 (2000)]; in: *Particles and Cosmology*, Proc. 10th Int. Baksan School, eds. E.N. Alexeev e.a., INR, Moscow (2000), p. 44.
- [26] A. A. Gvozdev and I. S. Ognev, Pis'ma v ZhETF **69**, 337 (1999) [JETP Letters **69**, 365 (1999)]; ZhETF **121**, 1219 (2002) [JETP **94**, 1043 (2002)].
- [27] R. C. Duncan and C. Thompson, Astrophys. J. **392**, L9 (1992).
- [28] P. Bocquet, S. Bonazzola, E. Gourgoulhon and J. Novak, Astron. Astrophys. **301**, 757 (1995).
- [29] C. Y. Cardall, M. Prakash and J. M. Lattimer, Astrophys. J. **554**, 322 (2001).
- [30] G. S. Bisnovaty-Kogan, Astron. Zh. **47**, 813 (1970) [Sov. Astron. **14**, 652 (1971)].
- [31] N. V. Ardeljan, G. S. Bisnovaty-Kogan and S. G. Moiseenko, Mon. Not. Roy. Astron. Soc. **359**, 333 (2005).
- [32] V. S. Imshennik and D. K. Nadyozhin, Usp. Fiz. Nauk **156**, 561 (1988) [Sov. Sci. Rev., Sect. E **8**, 1 (1989)]; D. K. Nadyozhin, in: *Particles and Cosmology*, Proc. 6th Int. Baksan School, eds. V.A. Matveev e.a., World Sci., Singapore (1992), p. 153.